Evaluating the effects of initial stocking, physiological age and species on wood stiffness

---

A dissertation submitted in partial fulfilment

of the requirements for the degree of

Bachelor of Forestry Science with Honours

By

L. T. Watson

New Zealand School of Forestry

University of Canterbury

Christchurch

New Zealand

2013

Abstract

The influence of initial stocking and physiologically aged cuttings (taken from 1-year-old and 5-year-old parents) on corewood modulus of elasticity (MOE) in 6-year-old *Pinus radiata* D. Don was studied in a Nelder-design experiment in Rolleston, Canterbury. In the same experiment, the influence of initial stocking on MOE in 5-year-old *Eucalyptus nitens* was also investigated. The study incorporated 19 different stocking levels ranging from 207 to 40,446 stems/ha. Green dynamic modulus of elasticity was assessed in standing trees using the TreeTap stress-wave method over the lower part of the stem (0.3 – 1.9m) for 151 *P. radiata* trees and 115 *E. nitens* trees.

The interaction between species and stocking significantly influenced MOE ($P<0.001$). MOE of *P. radiata* increased by 55% (or 3.9 GPa) between 271 and 40,466 stems/ha, and by 41% (or 2.2 GPa) between 271 and 4370 stems/ha. MOE of *E. nitens* was also influenced by stocking but the slope was significantly lower indicating that the effect of stocking was less pronounced than for *P. radiata.* Over the usual range of stockings for *E. nitens* there was an insignificant relationship between stocking and stiffness ($P=0.335$). Trees were also assessed for DBH, height, and stem slenderness (height/ DBH). None of these latter variables had a significant influence on MOE after the effects of stocking and species were accounted for. No effects of physiological age of cuttings were detected in this study.

The findings of this study highlight the importance of stocking as a tool that forest managers can utilize to regulate corewood stiffness in *P. radiata* trees. These results also suggest that for *E. nitens*, where wood stiffness is a priority, forest managers could reduce establishment costs by planting at much lower initial stockings. This study also highlights the superior stiffness of *E. nitens* in direct comparison with *P. radiata*, with many trees in the experiment already exceeding stiffness thresholds for structural timber in New Zealand.

Key words: Green dynamic modulus of elasticity, Wood stiffness, Corewood, *Pinus radiata*, *Eucalyptus nitens*, Initial stocking, Physiological age, Silviculture, Species by stocking interaction.

Table of Contents

List of Figures

List of Tables

List of Appendices

Acknowledgements

First and foremost I would like to thank my supervisor Euan Mason for his assistance with this study. His time, patience and support throughout the duration of my dissertation study were very much appreciated. I would also like to thank Marcel Van Leeuwen, Andree Callahagn and Sarah Naylor for their assistance with data collection. I would like to thank my family for their support and encouragement. Finally big thanks must go to my fellow class mates for providing endless entertainment in the computer lab, having such a great group of people around made this dissertation study an even more enjoyable experience.

1.0 Literature Review

1.1 Background

Many large corporate forestry companies in New Zealand are now shying away from pruning in their *Pinus radiata* D. Don plantations in favour of structural regimes (Mason, 2012). The utilization of wood for structural applications is primarily determined by wood quality characteristics. The notion that wood from the corewood zone of *P. radiata* stems is of low quality is nothing new and is a widely accepted concept. The dramatic changes we have seen in wood quality from our *P. radiata* plantations over the last three decades are the direct result of radical changes in establishment and management practices such as significantly reduced rotation lengths and lower initial crop stockings. (Lasserre, Mason, & Watt, 2008).

Corewood has often been defined as the first 10 growth rings (Cown, 1992). In general, wood from the corewood zone is characterised by many undesirable wood characteristics including low density, thin cell walls, short tracheids with large lumens, high grain angle, and high microfibral angle (Cown, McConchie, & Young, 1991). Wood from this section of the stem is inferior for many applications. The physical and mechanical properties of corewood (low stiffness and strength) render it unsuitable for load bearing applications, and the inherent lack of dimensional stability makes corewood highly undesirable for appearance applications due to distortion caused by differential shrinkage within boards upon drying (Cown et al., 1991; Walker & Butterfield, 1996; Xu & Walker, 2004).

Although there have been substantial efforts in the field of research focusing on the issue of corewood, little is understood about the processes that lead to the production of corewood in trees (Mason, 2008). In the past many forestry companies in New Zealand, with the knowledge that high growth rates are often associated with lower wood quality, have opted to extend rotation lengths (Apiolaza, 2008). In the economic climate today, and with strong competition from other *P. radiata* producing countries such as Brazil and Chile who are who are producing comparable crops in as little as 20 years, New Zealand forestry companies are faced with the challenge of improving wood quality in our plantations. We now, more than ever, desperately need to develop a greater understanding of the effects of regulating wood quality, especially in the corewood zone, of our *P. radiata* plantations.

At the present time *P. radiata* is almost the only option for structural timber in New Zealand, with the exception of Douglas fir which has strength and stiffness comparable to *P. radiata*. The issues with wood quality from our *P. radiata* plantations are now creating significant opportunities for the New Zealand forestry industry to explore the possibilities of alternative species for our structural crops.

1.2 Stiffness

Wood quality in fast grown plantation species, especially in the corewood zone, is primarily influenced by intrinsic wood properties (Walker, 2006; Walker & Butterfield, 1996). Microfibril angle, that is the angle of the cellulose fibrils in the S2 layer relative to the tracheid axis, is the primary factor affecting the mechanical properties of wood. A higher MFA is directly correlated with a lower stiffness value. Stiffness expressed as modulus of elasticity is the key wood property affecting deflection under load, and is generally considered to be more important than strength in engineered wood structures. Stiffness is the primary criterion in machine stress grading (MSG) of structural timber and is therefore the primary factor determining the utilization of wood for structural purposes (Walford, 1985). For the lowest grades of structural timber i.e. No. 1 Framing and MSG 6, a minimum average stiffness of 6 Gigapascals (GPa) is required, while a minimum average stiffness of 8 GPa and 10 GPa is required for the higher structural grades. Often, boards cut from the corewood zone of *P. radiata* stems do not meet these stiffness thresholds (Moore, 2012).

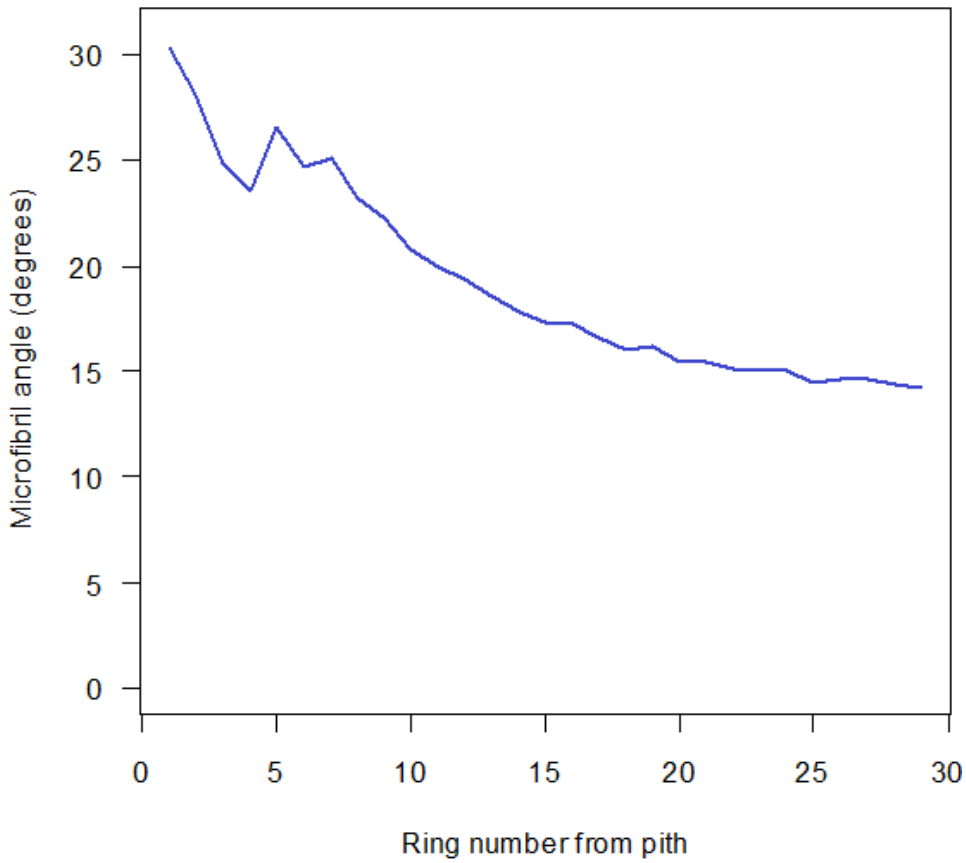


Figure 1: Microfibril angle vs. ring from pith at breast height in the Central North Island. Source: Mason and Dzierzon (2007).

Figure 1 demonstrates the typical pattern of microfibril angle (MFA) from pith to bark in a *P. radiata* stem. It clearly shows a significantly greater MFA (and therefore lower stiffness) in the corewood zone. More importantly, this figure demonstrates the sharp gradient in MFA from pith to bark that flattens out as you move into the outerwood. This highlights how stiffness varies greatly within *P. radiata* stems. The sharp gradient in MFA is also the factor determining the low dimensional stability in boards cut from the corewood zone of stems. Boards cut from this section of the stem are particularly unstable due to one side of the board having a substantially higher MFA than the opposing side of the board. This translates to differential shrinkage within boards resulting in defects such as crook, bow, twist which render the wood unsuitable non-structural applications such as cladding where high dimensional stability is required (Huang, Lindstrom, Nakada, & Ralston, 2003; Walker & Butterfield, 1996; Xu & Walker, 2004).

The value of sawn timber products is strongly related to wood quality traits such as stiffness, which is what is most concerning for the forestry industry. This was especially well illustrated by Sorensson and Shelbourne (2005) who plotted the value of logs against wood stiffness. A non-linear relationship between stiffness and value was the key point in this diagram which highlights the severe financial penalties incurred for not reaching the stiffness thresholds. This diagram showed that a significant economic gain can be made through meeting structural specifications, but it also demonstrated that additional gains diminish rapidly as you progress into the higher structural timber grades. Indicating that the most significant gains would made by lifting low stiffness timber up and over the structural timber thresholds.

The MFA of hardwoods lies well below that of many softwoods in the early years of tissue development. The practical implications of this suggest that Hardwood genera, such as *Eucalyptus,* are strong contenders where the target is to produce high quality sawn timber (Apiolaza et al., 2013). Hardwoods are generally not subject to the corewood issues of *P. radiata*. Instead there is a raft of issues associated with the utilization of hardwood species such as brittlewood, growth stresses, and collapse.

1.3 Acoustic tools

Significant costs are borne by the forestry industry with regard to wood processing. In the past it was often not until after costly processing that boards were, through destructive sampling techniques, deemed unsuitable for higher value structural grades. This presented a significant opportunity for economic gains through the assessment of wood properties such as stiffness prior to processing. In recent times the assessment of wood quality has been revolutionized (Xu & Walker, 2004). The introduction and adaptation of new non-destructive, cost-effective technologies for assessing the internal mechanics of stems has been driven by such desire to use wood more efficiently. Acoustic time-of-flight (ToF) tools are one such technology with proven capabilities for accurately, non-destructively assessing the mechanical properties of wood (Grabianowski, Manley, & Walker, 2004).

Acoustic tools utilize the strong relationship that exists between stress wave velocity and MOE to provide an accurate estimate of green stiffness in both standing trees and logs on the ground (Matheson, Dickson, Spencer, Joe, & Ilic, 2002). Portable ToF tools offer a fast and accurate measure for directly assessing stiffness in standing trees, even

at a very young age, using the fundamental equation (Equation 1) where MOE is the stiffness, ρ is green density (kg/m^{-3}) and V^2 is the measured acoustic velocity (m/s) squared (Grabianowski et al., 2004; Warren, Smith, Apiolaza, & Walker, 2009).

$$MOE = \rho * V^2 \quad (1)$$

In the present study the TreeTap tool, developed by Dr Michael Hayes of the Department of Electrical Engineering at the University of Canterbury, was used to asses stiffness in standing trees. This device essentially measures the transit time of an introduced stress wave between two sensory probes inserted into the stem at a known distance apart. The transit time is then used to calculate MOE.

1.4 Comparable studies

The influence of high initial stockings on stiffness in the corewood zone of *P. radiata* trees is widely acknowledged in the field research and has been shown to be consistent across a range of stand ages (Lasserre, Mason, & Watt, 2004; Lasserre et al., 2008; Waghorn, Watt, & Mason, 2007). Lasserre et al. (2008) assessed the influence of initial stocking (2500 stems/ha and 833 stems/ha) on corewood MOE in three *P. radiata* clones at two spatially separated sites in Canterbury. At the time of measurement trees were aged 11 years at site 1 and 9 years at site 2. The results showed that initial stocking had a highly significant ($P < 0.001$) effect on MOE with stress wave velocity readings in higher stocked plots exceeding values in the low initial spacing plots by 37% (1.8 GPa) at site 1 and 31% (1.5 GPa) at site 2. In another study by Lasserre et al. (2004) the effects of initial stocking on stiffness were evaluated for three stocking densities (833, 1250 and 2500 stems/ha) in 11 year old *P. radiata* at a Dalethorpe site in Canterbury. In this study stiffness values for the higher stocked plots greatly exceeded that of the lower stocked plots, with a 42% increase in stiffness from the lowest stocked plots (4.1 GPa) to the highest stocked plots (5.9 GPa). Similarly, a study by Waghorn et al. (2007) found outerwood MOE to be significantly influenced by initial spacing ($P < 0.0001$) in 17-year-old *P. radiata*. MOE increased by 39% from 5.4 to 7.5 GPa, between 209 and 2551 stems/ha. Most of the increase in MOE occurred between 209 and 835 stems/ha (MOE of 7.2 at 835 stems/ha). In contrast to previous studies, Grabianowski et al. (2004) found no significant difference in outerwood MOE between two stocking densities (100 and 625 stems/ha) in a study assessing the impact of stocking on outerwood MOE of 27-year-old *P. radiata* at Eyrewell Forest in Canterbury.

In various studies (Lasserre et al., 2008; Waghorn et al., 2007) stem slenderness, expressed as height divided by diameter at breast height, has been strongly correlated with stiffness at the base of stems. Watt et al. (2006) explains the theory behind the relationship between stiffness and slenderness. With increasingly higher stockings, stems become more slender due to competition for essential resources (light, water, nutrients and space to establish roots). These slender stems need to be stiffer, in comparison with short-wide stems in order to reduce the risk of stem buckling. Stocking also impacts upon the physical environment that trees are exposed. This is especially true with regard to windspeed within the canopy. A study by Grabianowski et al. (2004) found the effects of stocking on wind to have a significant impact on outerwood stiffness.

Results from previous studies suggest that deploying physiologically aged cuttings of a greater maturation status (physiological age) significantly improved MOE. Waghorn et al. (2007) evaluated the influence of tree morphology on outerwood MOE in 17-year-old *P. radiata* in a Nelder experiment located new Burnham, Canterbury. This experiment evaluated two separate lines of cuttings of different maturation status. Physiologically aged cuttings were from 1 and 3 year old pine parents. MOE of the cuttings of greater maturation status (7.7 GPa) was significantly greater than that of the cuttings from 1 year old pine parents (6.7 GPa). Similar conclusions are drawn by Menzies, Faulds, Holden, Kumar, and Klomp (2004) who conducted a study in the Bay of Plenty comparing five cutting treatments with physiological ages ranging from 1 to 5 years for three different seedlots. The results of this study showed that MOE at breast height increased with increasing physiological age, and was significantly greater than any other cutting trialled. In this study significant improvements in butt log straightness and decrease in malform rates were also observed with increasing physiological age.

The New Zealand forest industry has experimented with various alternative species to *P. radiata*, none of which are currently in extensive use. Hardwood species, *Eucalyptus* in particular, are strong candidates for short rotation plantations targeting high stiffness (Warren et al., 2009). *Eucalyptus* is a fast growing hardwood genus used in plantation forestry around the world. The stiffness properties of many hardwoods are far superior to that of softwoods (Yang & Evans, 2003). In general, MFA in hardwoods is relatively low (10-30^{o}) in comparison with that of softwoods (25-50^{o}) (Warren et al., 2009). Warren et al. (2009) investigated the effects of stocking on wood stiffness (MOE) for three *Eucalyptus* species (*E. cloeziana, E. pilularis and E. dunnii*) in a 6-year-old trial in

New South Wales, Australia. This study indicated that stocking significantly affected tree stiffness, but only at lower stocking rates. There was a significant increase in stiffness (around 11%) for all three species between 714 and 1,250 stems/ha, above the 1,250 stems/ha stocking rate the increase is stiffness between stocking levels was generally insignificant. These results have significant implications for forest managers, suggesting that little is to be gained, in wood stiffness, by planting initial stockings greater than 1250 stems/ha. In practical terms this indicates that in order to get the maximum wood quality benefit whilst reducing costs, stocking rates need not exceed 1250 stems/ha in plantations of *Eucalyptus* species.

2.0 Study objectives

This study aims to provide us with a better understanding of the underlying processes that influence wood quality in the corewood zone of *Pinus radiata* trees. This will provide forest managers with the knowledge to aid them in developing reliable models for predicting wood quality in our plantation forests which will ultimately allow the New Zealand forestry industry to improve wood quality in our short rotation *P. radiata* plantations. We also assess the effects of stocking in *Eucalyptus nitens* and evaluate the potential of *E. nitens* as a potential alternative species to *P. radiata* in structural regimes.

The formal objectives of this study are:

Primary objective

- To test the hypothesis that corewood stiffness will increase as stocking increases, and be higher for physiologically aged cuttings.

Aim of the primary objective

- To assess if forest managers should increase initial crop stockings, or use physiologically age cuttings as methods of regulating corewood stiffness in *P. radiata* trees.

Secondary objective

- To test the hypothesis that stiffness will increase with increasing stocking, and be higher for *E. nitens* in comparison with *P. radiata*.

Aim of the secondary objective

- To assess the affects of initial stocking in *E. nitens*, and to evaluate *E. nitens* as a potential alternative species to *P. radiata* in structural regimes by making a direct comparison between the two species.

3.0 Materials and methods

3.1 Site description

The measurements for this study were taken from *P. radiata* and *E. nitens* trees growing in a Nelder experiment (Nelder, 1962), located approximately 4 km South of Rolleston, Canterbury, New Zealand. The trial was located on a Chertsey loam (Kear, Gibbs, & Miller, 1967) and experienced a mean annual rainfall of 600-700 mm (Molloy & Christie, 1993).

3.2 Experimental design and treatments

The experimental design follows that outlined by Nelder (1962). The experiment comprises of 45 spokes separated by 8 degree intervals (Figure 2). In total there are 24 rows of *P. radiata* (456 trees) and 21 rows of *E. nitens* (399 trees). There are 21 circular rings which each represent a different stocking level (Table 1). In this study we evaluate 19 of the 21 circular rings corresponding to stocking levels ranging from 271 stems/ha to 40,466 stems/ha. The very outside and inside rings are excluded from the analysis so that each tree has a full set of neighbors and is therefore, theoretically, subjected to the same or similar conditions. The experiment contains two species (*Pinus radiata* and *Eucalyptus nitens*). The *P. radiata* trees are one year older than the *E. nitens* trees and were planted in 2007 (now 6 years old) while the *E. nitens* trees were planted in 2008 (now 5 years old). The *P. radiata* trees are also set up in a randomised complete block design, that comprises of four complete blocks, each with three adjacent rows of cuttings taken from 1 and 5 year old pine parents, to facilitate the assessment of physiologically age on wood stiffness (Figure 2). Only the centre row of each group of three was assessed, while the other rows were used as buffers.

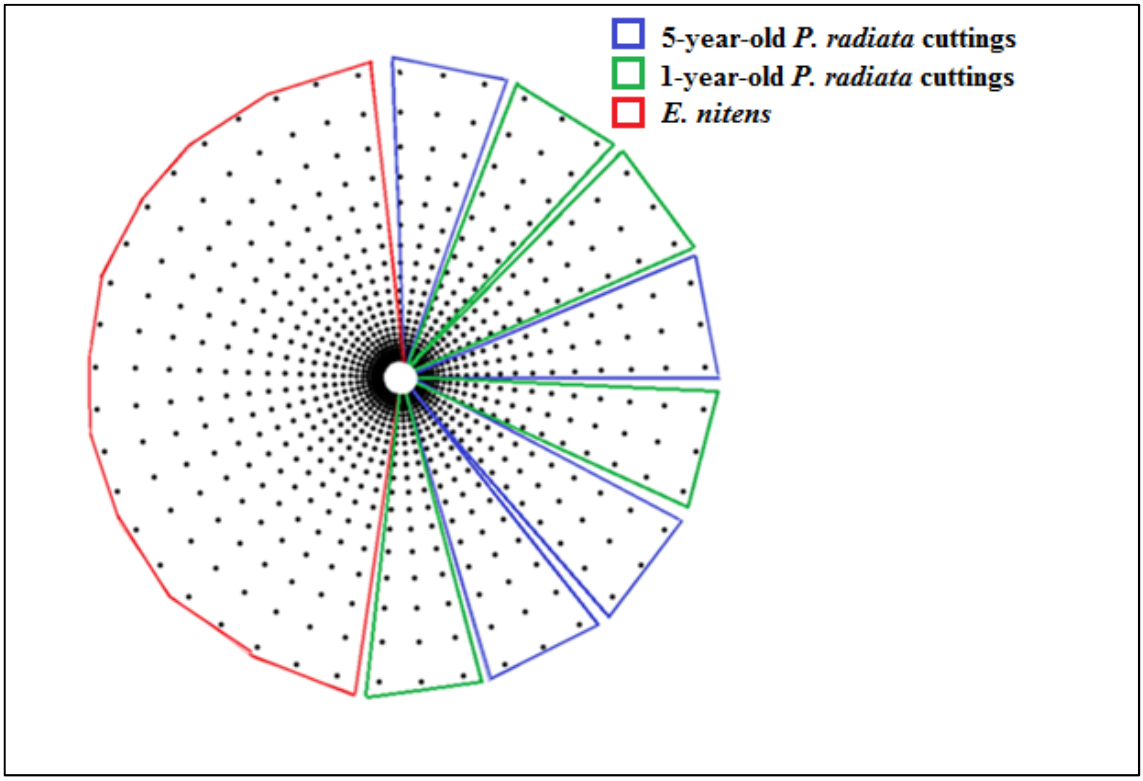


Figure 2: Nelder design. Note that each dot in the graph represents a tree.

Table 1: Nelder stocking design.

Ring number	Stocking (stems/ha)
Buffer	-
1	271
2	357
3	472
4	623
5	823
6	1,087
7	1,436
8	1,897
9	2,505
10	3,309
11	4,370
12	5,772
13	7,623
14	10,069
15	13,298
16	17,564
17	23,198
18	30,639
19	40,466
Buffer	-

Table 2 shows the individual trait ratings sourced from the seed certificates for each of the aged cuttings in this experiment. The cuttings for this experiment were sourced from separate seed orchards. The 1-year-old cuttings were from Proseed at Amberley, and the 5-year-old cuttings were from Olsen Seed at Seddon. The 1-year-old cuttings were the offspring of 43 parents intermated (crossed) 66 times, and the 5-year-old cuttings were the offspring of 10 parents crossed 9 times and therefore have a narrower range of genotypes. Both cuttings in the experiment are rated as GF 24.

Table 2: Individual trait ratings for each of the P. radiata cuttings.

	Growth	Straightness	Branching	Dothistroma	Wood density	Spiral grain
1-year-old cuttings	22	20	22	18	23	21
5-year-old cuttings	22	21	22	20	26	21

3.3 Measurements and calculations

Measurements of stem height and diameter were taken for all trees in the experiment (456 *P. radiata* stems and 399 *E. nitens).* Diameter was measured at breast height (1.4 m) using a diameter tape and tree height was measured with a height pole to the nearest 10 cm. Stem slenderness was calculated by dividing measured tree height by diameter at breast height (DBH) for each tree.

Stiffness was measured for a representative sample of rows for each species (8 rows of *P. radiata* and 7 rows of *E. nitens*). The middle of each of the *P. radiata* blocks was measured, while every third row starting with the second row in was assessed in the *E. nitens*. Measurements of stiffness were taken for all trees with a DBH greater than 3cm. Due to the nature of the TreeTap probes (size and design of the probes) assessing smaller trees was difficult as the probes were not able to be accurately inserted into the stem. As such one *P. radiata* tree and 18 *E. nitens* trees were excluded from the study. *E. nitens* trees in the center of the experiment at very high stockings often tended to be too small (<3cm DBH) or dead (no green crown remaining). A total 151 *P. radiata* stems and 115 *E. nitens* trees were assessed for stiffness.

Measurements of tree stiffness were collected using the TreeTap ToF tool (Version 1, University of Canterbury, New Zealand). The two receiver probes were lightly hammered into each stem at a 45^{o} angle relative to the stem with both probes angled down. The probes were inserted at approximately 0.6 and 1.9 m from the ground. A third probe, a metal spike, was then inserted at an opposing angle to the two receivers at 20 cm below the lower of the two probes. The third probe was lightly tapped with a hammer to generate the required acoustic stress wave. This process was repeated for each side of the tree (it should be noted that no preference was given to what side of the tree probes were inserted i.e. leeward and windward), thus allowing for differences in stiffness between each side of the tree due to things such as leaning trees. 6 taps per side

(a total of 12 taps per tree) were recorded to ensure the reliability and accuracy of measurements as transit time had the tendency to vary ever so slightly between taps. Variation between taps occurs due to phenomena such as not hitting the third probe square on the head or a foreign object touching the probe during the tap, thus causing a miss reading on the TreeTap. Identifying misrepresentative data was a simple task undertaken in the field. We worked in pairs so that one person operated the TreeTap machine and watched for irregular recordings, while the other inserted the receiver probes and tapped the start probe. Where taps were wildly irregular, such that the TreeTap unit indicated a miss reading, or visual identification of miss readings (with transit times often much higher than usual), that particular tap was manually deleted from the TreeTap unit and a second tap was recorded as a replacement.

The transit time value used for analysis was the average value for the measurements taken on opposing sides of each tree. To calculate stiffness, the transit time was then converted to acoustic velocity (km/s) by dividing the distance the acoustic signal had to travel between the probes in meters (1.3m for all measurements of stiffness) by the transit time in seconds (Equation 2).

$$Acoustic\ velocity\ \left(\frac{km}{s}\right) = \frac{0.0013\ \text{km}}{\text{average transit time in seconds}} \quad (2)$$

The acoustic velocity for each tree was then used to estimate the stiffness (in Gigapascals, GPa) of each tree (Equation 3).

$$\textit{Stiffness (GPa)} = \textit{MOE} = (\text{acoustic velocity})^2 \times \text{green density} \quad (3)$$

Green density in *P. radiata* trees is often assumed to remain constant in both sapwood and heartwood as trees age, but as sapwood is converted to heartwood the green density drops (Cown et al., 1991). In general green densities of *P. radiata* sapwood between 1000 and 1100 kg m^{-3} have been either used (Grabianowski et al., 2004; Lasserre et al., 2004), or calculated through core samples in past studies (Lasserre et al., 2008). Due to the apparent low variation in green density a value of 1000 kg m^{-3} is often used. Similarly, there appears to be very little variation in green density of *E. nitens* sapwood. Warren et al. (2009) assumed a green density of 1100 kg m^{-3} in a study examining the effects of stocking on stiffness for three *Eucalyptus* species (*E. cloeziana, E. pilularis*

and E. dunnii). Chauhan (2004) used billet samples of 10 year old *E. nitens* located on the Port Hills, Christchurch to determine green density in the lab. A mean green density of 1124 kg m^3 was calculated which supports the value assumed by Warren et al. (2009). For the purpose of this study it was appropriate to assume a constant green density value of 1000 kg m^3 for *P. radiata* and 1100 kg m^3 for *E. nitens* due to the low variation in this property which leaves only a small chance for error in MOE.

The TreeTap tool is only designed to measure the stiffness within the outer few rings (around 5mm) as the probes do not penetrate further than this into the stem (Lasserre et al., 2004). However, this is not an issue for this study for either *P. radiata* or *E. nitens*. The *P. radiata* trees are only 6 years old and therefore theoretically have no outerwood. The TreeTap assesses the stiffest wood in the stem as the acoustic wave travels fastest in this tissue, in this study the wood adjacent to the bark is the "corewood". Likewise there is no reason for concern with regard to measurement of the *E. nitens* as tissue formation in hardwood differs greatly to that of softwoods, and as such, the terms corewood and outerwood are not usually applied to hardwood species.

3.4 Data analysis

The stiffness data were then collated in a Microsoft Excel spread sheet along with the data from growth variable measurements (height, DBH, and slenderness). *Box-cox* transformations (Cook & Weisberg, 2009) were used on both response and independent variables to linearize curvilinear relationships between response and independent variables, to normalise the residual distributions, and to stabilise the variance and avoid heteroscedasticity. Below is the basic function of a *Box-cox* transformation where *x* is a continuous function of • (Equation 4).

$$x^{(\lambda)} = \begin{cases} (x^{\lambda} - 1)/\lambda & \lambda \neq 0 \\ \log(x) & \lambda = 0 \end{cases} \quad (4)$$

All statistical analyses for this study were undertaken using the statistical package R. Two separate linear regression analyses were undertaken. The first regression analysis evaluated the effects of stocking or other candidate variables such as slenderness or DBH as the primary variable representing competition as predictors of stiffness for both species. The second regression analysis was carried out for just *P. radiata*, and a

dummy variable for aging was used to assess the effects of aging on wood stiffness. To verify the results of the regression analysis of the aging affect a mixed effects analysis was conducted. This entailed including the block term as a factor representing the four paired replicates of 1 and 5 year old parents for pine cuttings.

Where significant relationships were observed between important model variables analysis of multi-collinearity (Cook & Weisberg, 2009) was conducted. This involved fitting the residuals of y (MOE) as a function of x1 (predictor variable 1). Then fitting x2 (predictor variable 2) as a function of x1 to show what information in x2 is not present in x1. If the information in x2, that is not in x1 is correlated with the information in y not in x1 then there is a good case to have x2 in the model alongside x1 because it contains information that is relevant to y that is not contained in x1. Variance inflation factors (VIF) were also used to quantify the severity of multi-collinearity.

Stiffness measurements may have been influenced by branching. Branches intercept the soundwaves used by the TreeTap machine as the fibres around the branches are oriented in a different direction to the way that the soundwaves are travelling. Further analysis was conducted that involved examining the relationship between branching variables (branch basal area and number of branches per tree) and measured stem stiffness. The data for this analysis were kindly provided by Sarah Naylor who was concurrently completing a study in the Nelder experiment investigating the effects of stocking and physiological age on branching and tree form. The rows sampled for this dataset are shown in Figure 3. Branch basal area and the number of branches were calculated for the 1.3m section of stem for which the tree tap measurements were taken (i.e. branches between 0.6 and 1.9m up any given stem).

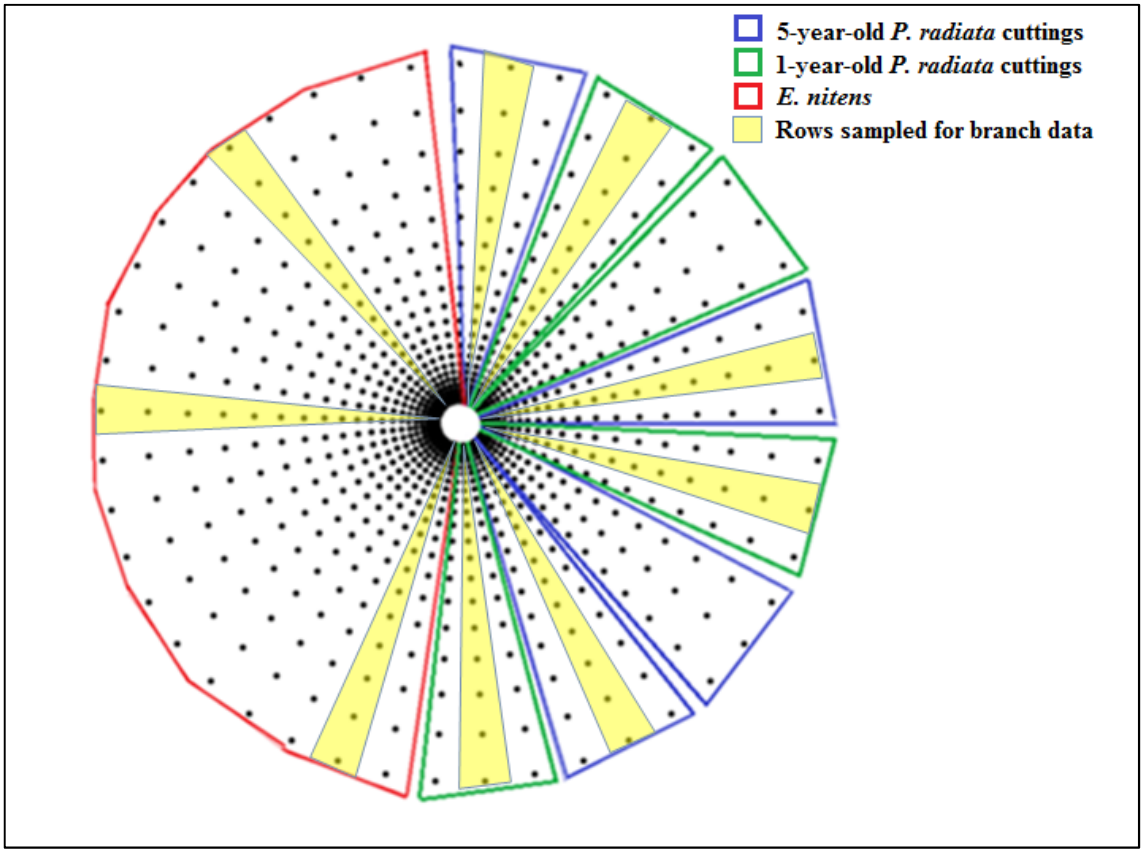


Figure 3: Visual representation of the data collected to analyse the branching effects.

4.0 Results

4.1 The effect of stocking on tree dimensions

Differences in tree dimensions (height, DBH and slenderness) with changes in stand stocking were observed between the two species. At the lower stocking tree height in *E. nitens* trees was greater than in *P. radiata* trees at the same stocking level, while at the higher stockings there was a less noticeable difference in tree height (Figure 4). The effects of stocking on tree height were significantly less in the *P. radiata* trees as indicated by the flatter slope of the line.

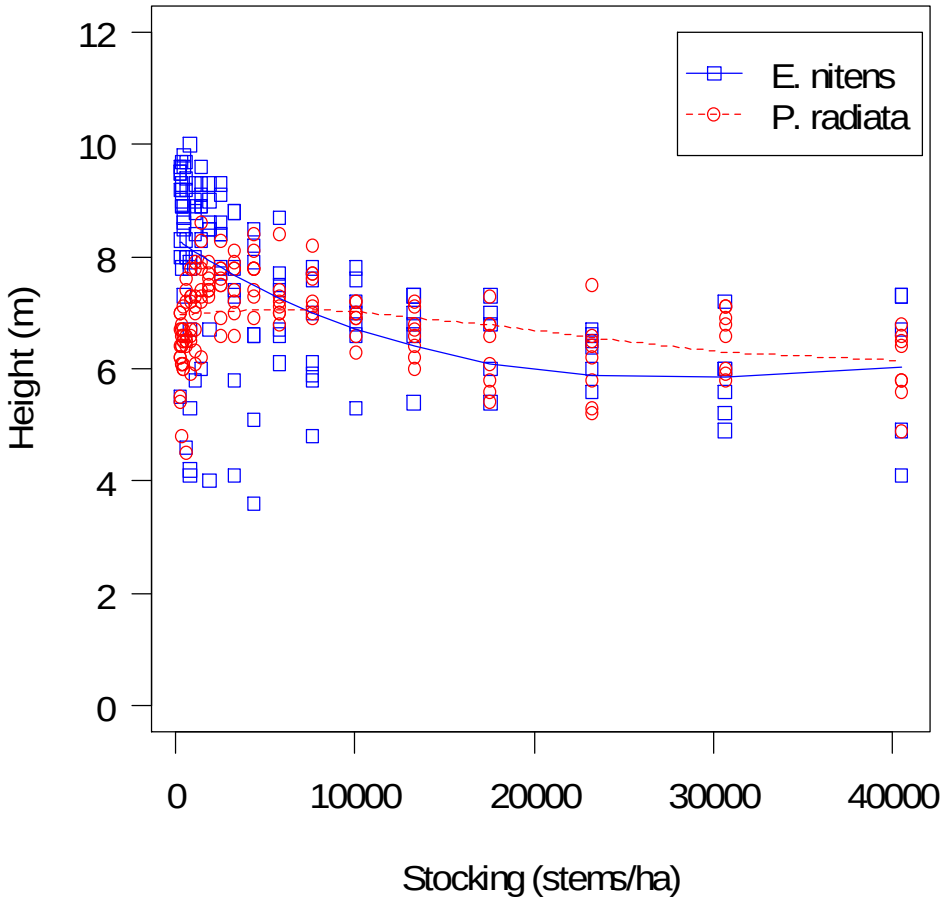


Figure 4: The relationship between stocking and tree height.

The relationship between DBH and stocking followed a similar pattern for both tree species. In both species DBH was much lower at higher stocking levels (Figure 5). The effects of increasing stand stocking on DBH were apparent until around 15,000 stems/ha at which point DBH remains relatively constant for both tree species. There was far greater spread in DBH observed for *E. nitens* trees in comparison with *P. radiata.*

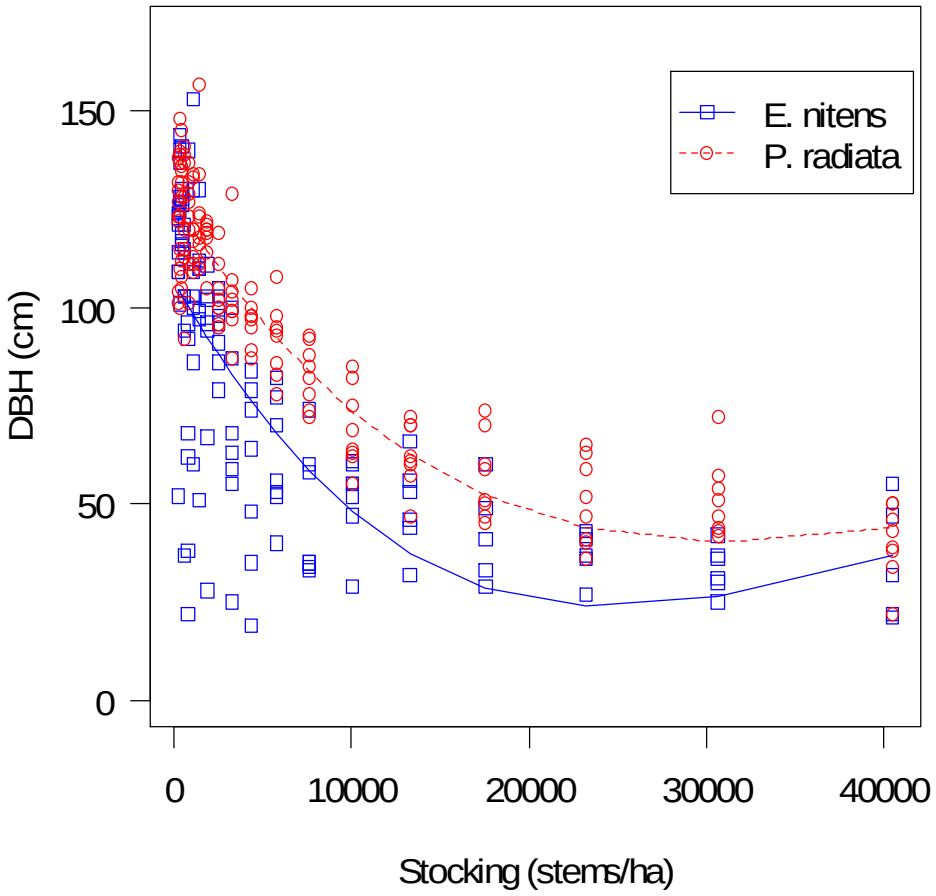


Figure 5: The relationship between stocking and diameter at breast height .

There was a strong positive curvilinear relationship between stocking and slenderness for both tree species (Figure 6). This indicated that stocking and slenderness could not be included together in a model for predicting MOE due to multi-collinearity. Analysis of multi-collinearity showed that stocking was a more powerful predictor of MOE for this dataset. The variance inflation factor (VIF = 9) supported this result.

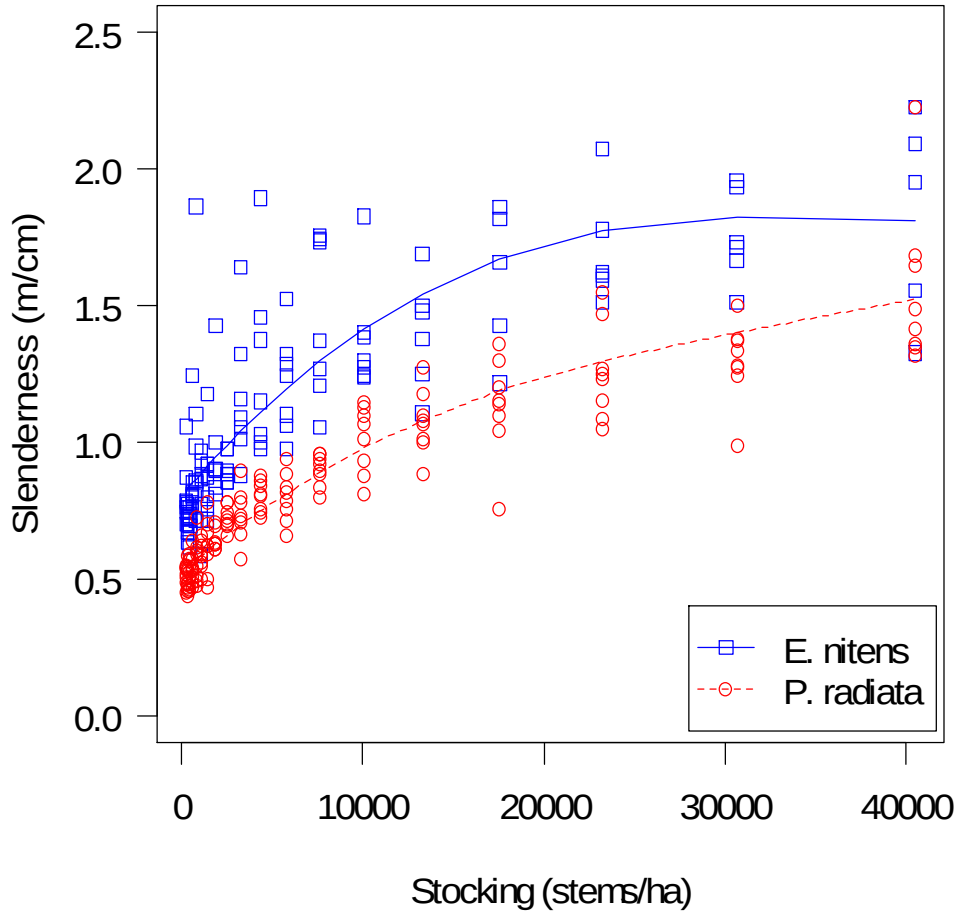


Figure 6: The relationship between stocking and slenderness.

4.2 The combined model for the stocking and species effects

A combined model of MOE with stocking and species showed that there was a significant interaction in the effect of stocking and species on MOE ($P<0.001$). There was a marked difference in slope between species for the relationship between stocking and MOE (Figure 7). The slope of the line for *P. radiata* was significantly greater than for *E. nitens*. This tells us that MOE in *P. radiata* trees increases more rapidly as stocking increases than MOE in *E. nitens* tree does.

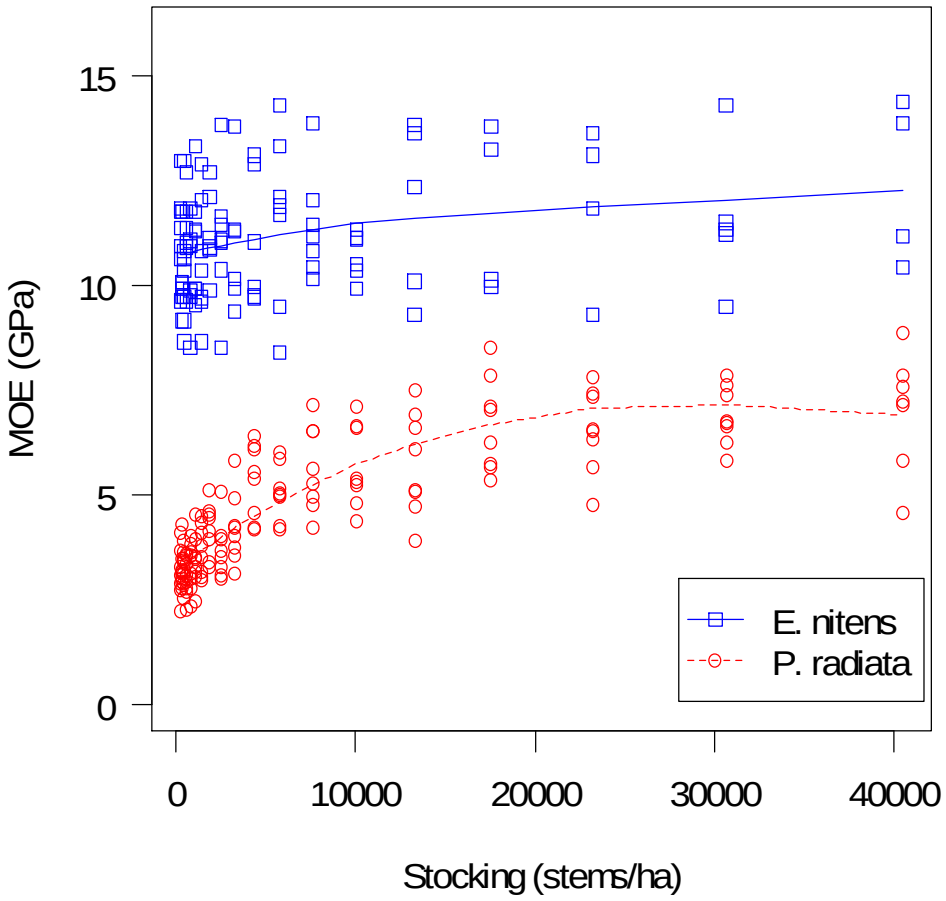


Figure 7: The relationship between stocking and MOE.

4.3 The effects of stocking, DBH and height on wood stiffness

There was a significant difference in the level of stiffness between the two tree species. On average MOE in *E. nitens* trees was twice that of *P. radiata trees* (Figure 7). To put these results into perspective for forest managers, the relationship of MOE and stocking by tree species was also plotted over a reduced range of stocking levels (271 and 44,466 stems/ha) which were assumed to represent the usual range of stockings for silvicultural

regimes in New Zealand plantations. The significant difference in level of MOE was also apparent over the reduced range of initial stockings (Figure 8).

In *P. radiata* trees stocking had a highly significant influence on MOE ($P<0.001$). MOE values at the highest stocking level (44,460 stems/ha) exceeded that of the lowest stocking level (271 stems/ha) by 55% (or 3.9 GPa). MOE was also significantly influenced by stocking in *E. nitens* trees ($P=0.003$). Over the reduced stocking range, the effect of stocking on MOE in *P. radiata* trees was also significant ($P<0.001$) with MOE at the 4370 stems/ha exceeding that of the lowest stocking (271 stems/ha) by 41% (or 2.2 GPa). However, there was an insignificant relationship between stocking and MOE over same reduced range of stockings in *E. nitens* trees ($P=0.335$).

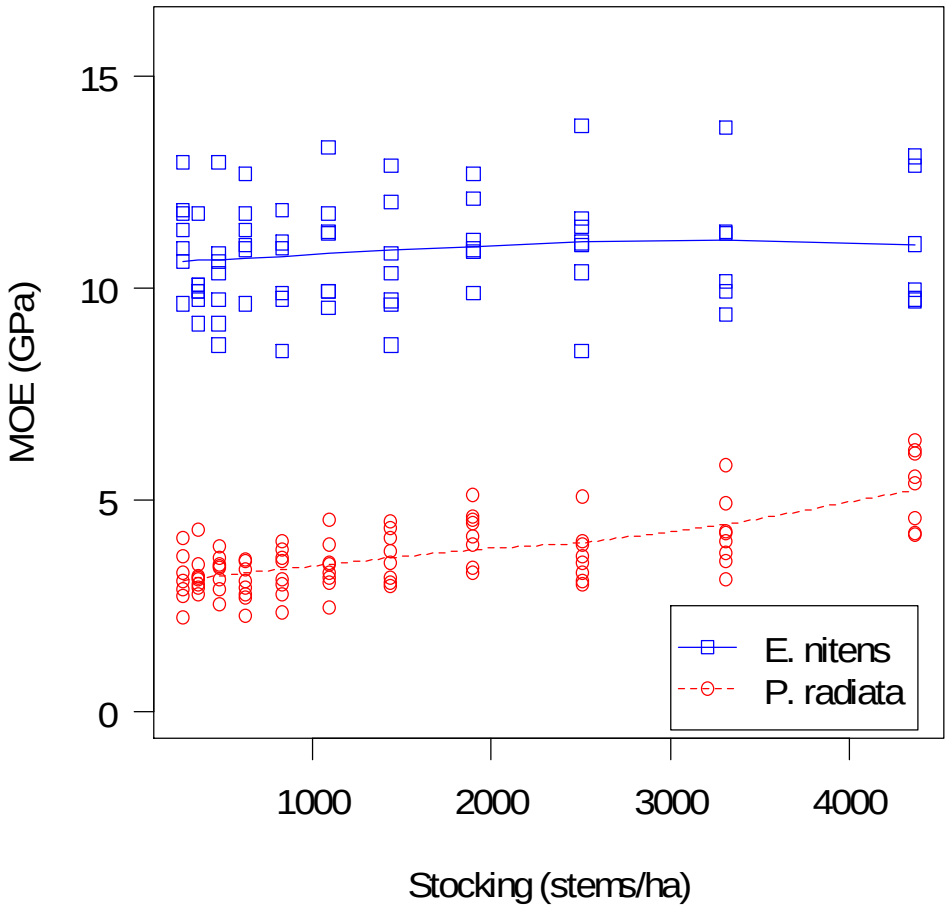


Figure 8: The relationship between stocking and MOE for stockings assumed to be realistic for New Zealand silvicultural regimes (271 to 4370 stems/ha).

Among the *P. radiata* trees there was a highly significant (P<0.001) relationship between DBH and MOE (Appendix 1), with DBH explaining a moderate proportion of the variation in MOE (R^2 = 0.614). However, DBH was strongly correlated with stocking and further analysis showed that there was no relationship between DBH and model residuals after the effects of stocking were accounted for. DBH added very little predictive power to the model, and for this reason DBH was not included in further models. The relationship between tree height and MOE in *P. radiata* highly insignificant (P=0.74) (Appendix 2).

The effects of DBH and height were also tested for their relationship with MOE in the *E. nitens* trees (Appendix 1 & 2). DBH and height were both insignificant in predicting MOE (P= 0.158, and P=0.164 respectively).

4.4 The age effect

Regression analysis assessing the effects of physiological age of *P. radiata* cuttings on MOE showed that the effect of physiological age on corewood MOE was insignificant ($P<0.05$). Figure 9 provides a visual representation of the relationship between stocking and MOE for each age treatment. It shows that the data were considerably scattered and that there was no apparent difference between the age treatments.

The results of a mixed effects analysis supported this finding. This analysis showed that the physiological age of *P. radiata* cuttings had no effect on MOE.

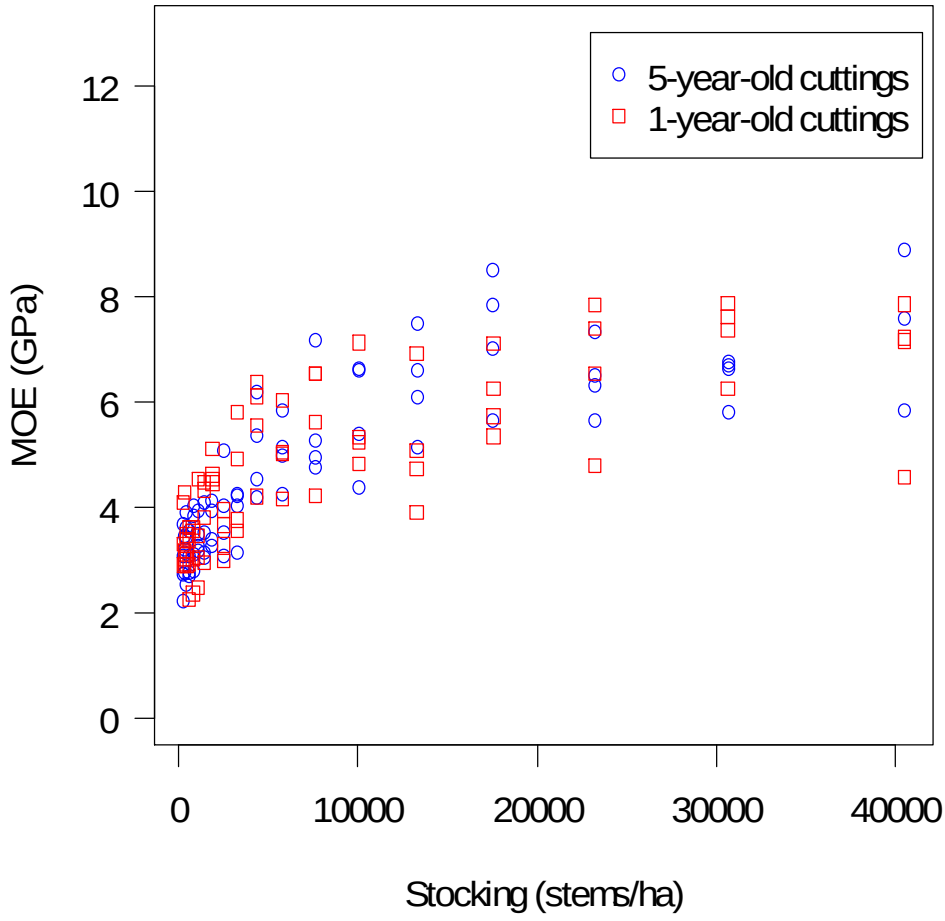


Figure 9: The relationship between MOE and physiological age of radiata pine cuttings.

4.5 Analysis of the effect of branching on stiffness

There was significant variation in branch basal and the number of branches per tree in both species (Table 3). In *P. radiata* trees there was also significant variation in the number of branches per tree. However there was significantly less variation in branch basal area per tree for *E. nitens* trees.

Table 3: Branching descriptive statistics.

		Mean	**Standard deviation**	**Min**	**Max**
P. radiata	**Basal area (m^2)**	1.06	3.77	0.00	39.69
	Number of branches	24.27	9.53	6.00	50.00
E. nitens	**Basal area (m^2)**	0.14	0.10	0.01	0.55
	Number of branches	16.17	5.69	3.00	31.00

There was a reduction in branch basal area per tree with increasing stand stocking (Appendix 3). The effect of stocking on branch basal area was more pronounced in the *P. radiata* trees. There was a significantly lesser effect of stocking on branch basal area per tree in the *E. nitens* (Appendix 3). In both species, the number of branches per tree reduced with an increase in initial stocking (Appendix 4).

There was no relationship between either of the branching variables (branch basal area and branch number) and model residuals after the effects of stocking were accounted for in the model of MOE.

5.0 Discussion

5.1 The stocking and species effects

The most significant finding of this study was that species and stocking were interacting in their effects on MOE. This clearly showed that MOE of the two trees species in this study responded differently to increasing stand stocking. MOE in *P. radiata* trees was much more sensitive to increases in stocking in comparison with *E. nitens* trees.

The effect of stocking on MOE was clear for *P. radiata*. A 55% increase in average MOE was recorded between 271 and 40,466 stems/ha. While a 41% increase in average MOE was observed between 271 and 4370 stems/ha. The finding that there was a significant effect of stocking on MOE at stocking levels that would be considered feasible in New Zealand plantation forests (271 to 4370 stems/ha) suggests that increasing initial stocking was an effective method that could be used by forest managers to regulate corewood MOE in *P. radiata* trees. This result is consistent with the findings of other researchers (Lasserre et al., 2004; Lasserre et al., 2008).

Stocking appeared to have a lower effect on MOE in *E. nitens* trees. The relationship between stocking and MOE was insignificant (P=0.335) over the reduced range of stockings studied (271 to 4370 stems/ha). This is inconsistent with the results of Warren et al. (2009) who observed a significant relationship between stocking and MOE, albeit at lower stocking levels. The implications of this suggest that, where MOE is a priority, forest managers can significantly reduce establishment costs by planting crops of *E. nitens* at lower initial stockings. However, from a wood processing perspective, wood quality with respect to MOE is not the only factor determining the utilization of wood for structural purposes. And, although this is beyond the scope of this study, the effects of stocking on other stem characteristics such as branch size and stem form must also be considered. At higher stockings branch size is kept to a minimum. Similarly, establishing crops at higher initial stockings allows for selection of the best crop trees and subsequent thinning out of poor performing trees. The process of thinning not only selects the best trees but also aids in achieving girth growth, and avoids excessive upwards growth which would result in tall slender trees which are more susceptible to toppling. Therefore the incurred cost of planting additional stems may in fact be compensated for through higher yields and higher quality logs.

Over all, a significant difference in the level of MOE (P<0.001) was also observed between the two species, with *E. nitens* trees consistently exhibiting greater wood

stiffness in comparison with *P. radiata* trees over the entire range of stockings assessed in this study. Even at a young age the *E. nitens* trees were already exceeding the stiffness thresholds for structural timber in New Zealand. This highlights the potential of *Eucalyptus* species and more specifically *E. nitens* as an alternative to *P. radiata* in structural regimes. This result of course fails to account for other important factors such as markets, and pest and disease susceptibility which would also need to be considered when choosing a species for a given site.

An interesting result of this study was the finding that stocking was more strongly related to MOE than stem slenderness. Including stocking as a covariate accounted for the significant effects of slenderness. This contrasts with the findings of Lasserre et al. (2008) and Waghorn et al. (2007) who found slenderness to be more strongly correlated with MOE than stocking.

5.2 The age effect

The advantages of establishing *P. radiata* crops with parents of a greater physiological age (which are considered to perform more like a mature tree) were found to be negligible in this study. This is a highly important result as establishing tree crops is an expensive business, and cuttings, more specifically those of a greater physiological age, are significantly more expensive in comparison with seedlings. For this reason, for physiologically aged cuttings to become a viable option for establishment, we would need to see significant gains in the performance of characteristics such as wood stiffness which were simply not observed in this study. This result is in direct contrast to the findings of previous researchers (Menzies et al., 2004; Waghorn et al., 2007) who reported significantly higher MOE in trees of a greater maturation status. In saying this, there is at present much discussion based around the effects of physiologically aged cuttings on MOE with many contrasting findings. It is not clear if the present result is representative of future years, but if there were significant differences between the two treatments then we may expect to see some differences appearing already. The measurements by Menzies et al. (2004) and Waghorn et al. (2007) were undertaken in 12 and 17-year-old trees respectively. It is therefore possible that the effects of physiological age on stiffness are yet to be expressed and may become apparent in future years.

For this purpose of this study the assumption was made that there would be no confounding effect in the analysis of the physiological age effects caused by the two *P. radiata* cuttings being from different families. In reality there is the chance that there was a confounding effect between genetics and physiological age, but the likelihood of this occurring is very low. The rational for this assumption was based on the fact that, 1) both cuttings are rated as GF24, 2) the rankings of individual traits on the seed certificates of each cutting were very similar, and 3) there are a large number of families for each cutting (43 parents for the 1-year-old cuttings, and 10 parents for the 5-year-old cuttings) and therefore the chances, according to the law of large numbers, are very small that we are seeing a strong genetic effect caused by all families for one cutting exhibiting an inherently low MOE and all cuttings for the other cutting exhibiting a high MOE.

5.4 The effects of branching on stiffness measurements

It was very interesting to find that despite there being significant variation in branching variables (branch basal area and branch number) within stocking levels in *P. radiata* trees (albeit at the lower stocking levels), and in number of branches for *E. nitens*, that there was no relationship of either of these variables with model residuals after the effects of stocking were accounted for. This would indicate that there were no effects of branching on stiffness measurements. However, there was a high degree of colinearity between stocking and both of the branching variables, and therefore branching may in fact have influenced the measurements of stiffness, and we may not be seeing this effect because of the relationship between stocking and branching variables.

5.5 Comparison with a previous study

It is very difficult to make an accurate comparison of the results of the present study with that of a previous study by Adam Sewell back in 2009. There are a few reasons for this. Firstly, he used a different machine to measure stiffness, the Fakopp ultrasonic timer. And secondly the trees were much younger at the time of his measurements, the *P. radiata* were 2 years old and the *E. nitens* were 1 year old which may explain some of the variability in his results. However, the basic trends observed in this study were the same as that of the previous study. MOE in *P. radiata* trees was also significantly influenced by stocking, but unlike in the current study, the effect of stocking was

insignificant over the same range of usual plantation stockings as assumed in this study. Stocking also significantly influenced stiffness in *E. nitens* trees, and again the effect of stocking was insignificant over the usual range of stockings. Similarly the finding that there was no effect of physiological age on wood stiffness in this study supports the findings of Adam Sewell in the previous study.

6.0 Limitations and potential future study

The sample size for the *E. nitens* trees was significantly reduced by the number of missing/dead trees in some of the *E. nitens* rows, especially at the higher stockings where competition was significantly greater. In total 18 *E. nitens* trees were excluded from the analysis as they were either dead (no green crown remaining) or too small (<3cm DBH). For the purpose of this study it was assumed that because there was very little change in MOE with changes in stocking in the *E. nitens* trees, there would be no significant impact on the overall conclusions drawn from this study.

Some very exciting results have come out of this study, but the trees were still relatively young and so wood grown in future years may not follow the trends reported here. Re-measurement of the trial in future years will be highly beneficial and will help to determine how the relationships of stocking and species with MOE change through time. It will also be very interesting to see if the null effect of physiological age of cuttings on MOE continues through time or whether there are any delayed effects that become apparent with time. If the lack of relationship between physiological age and MOE proved to be negligible in future years, this would have significant implications for managers.

7.0 Conclusion

The tree species (*P. radiata* and *E. nitens*) in this study responded very differently to changes in stand stocking. For *P. radiata* trees where increasing corewood MOE is the priority, increasing initial stocking may be an important tool that could be utilized by forest managers to regulate MOE in the corewood zone. This study revealed gains in MOE of 41% (or 2 GPa) by increasing initial stocking to the upper bound of what is considered feasible for *P. radiata* silvicultural regimes in New Zealand (4370 stems/ha). By contrast, MOE in *E. nitens* trees showed very little change in MOE with increases in stand stocking, indicating that there would be no practically signifcant gains in MOE by increasing initial stocking.

There were also significant differences in the level of stiffness between the two species, with *E. nitens* consistently producing stiffer timber than *P. radiata* even at a younger age (5 years old, compared to the 6 year old *P. radiata*). This study highlighted the superior wood stiffness characteristics exhibited by *Eucalypt* species, and provides evidence that managers might consider alternative species such as *E. nitens* where MOE is a priority.

In this study there were no observed gains in MOE in *P. radiata* cuttings that were propagated from five year old plants compared to those propagated from one year old plants.

8.0 References

Apiolaza, L. A. (2008). Improvement objectives for short rotation forestry. *New Zealand Journal of Forestry, 52*, 26-28.

Apiolaza, L. A., Chauhan, S. S., Hayes, M., Nakada, R., Sharma, M., & Walker, J. (2013). Selection and breeding for wood quality: a new approach. *New Zealand Journal of Forestry, 58*(1), 32-37.

Chauhan, S. S. (2004). Relationships between longitudinal growth strain and some wood properties in. *Australian forestry, 67*(4), 254-260.

Cook, R. D., & Weisberg, S. (2009). *Applied regression including computing and graphics* (Vol. 488): John Wiley & Sons.

Cown, D. J. (1992). Corewood (juvenile wood) in *Pinus radiata*-should we be concerned? *New Zealand Journal of Forestry Science, 22*, 87-95.

Cown, D. J., McConchie, D. L., & Young, G. D. (1991). Radiata pine: wood properties survey. *FRI Bulletin No. 50 (Revised edition)*, 55.

Grabianowski, M., Manley, B., & Walker, J. (2004). Impact of stocking and exposure on outerwood acoustic properties of Pinus radiata in Eyrewell Forest. *New Zealand Journal of Forestry, 49*(2), 13-17.

Huang, C. L., Lindstrom, H., Nakada, R., & Ralston, J. (2003). Cell wall structure and wood properties determined by acoustics - a selective review. *Holz als Roh und Werkstoff, 61*(5), 321-335.

Kear, B. S., Gibbs, H. S., & Miller, R. B. (1967). *Soils of the downs and plains Canterbury and North Otago, New Zealand*. Wellington.

Lasserre, J. P., Mason, E., & Watt, M. (2004). The influence of initial stocking on corewood stiffness in a clonal experiment of 11-year-old Pinus radiata D.Don. *New Zealand Journal of Forestry, 49*(2), 18-23.

Lasserre, J. P., Mason, E. G., & Watt, M. S. (2008). Influence of the main and interactive effects of site, stand stocking and clone on Pinus radiata D. Don corewood modulus of elasticity. *Forest Ecology and Management, 255*(8–9), 3455-3459.

Mason, E. G. (2008). Influences of silviculture, genetics and environment on radiata pine corewood properties: results from recent studies and future direstions. *New Zealand Journal of Forestry, 53*, 26-31.

Mason, E. G. (2012). Designing silvicultural regimes with a structural log index. *New Zealand Journal of Forestry, 57*(2), 13-18.

Mason, E. G., & Dzierzon, H. (2007). Radiata pine resource characterisation: Analysis of national benchmarking study, Wood Quality Intiative report RES35 (pp. 56).

Matheson, A. C., Dickson, R. L., Spencer, D. J., Joe, B., & Ilic, J. (2002). Acoustic segregation of Pinus radiata logs according to stiffness. [Conference paper]. *Annals of Forest Science, 59*(5), 471-477.

Menzies, M. I., Faulds, T., Holden, D. G., Kumar, S., & Klomp, B. K. (2004). Maturation status and genetic improvement effects on growth, form, and wood properties of Pinus radiata cuttings up to age 12 years. *New Zealand Journal of Forestry Science, 34*(3), 255-271.

Molloy, L., & Christie, Q. R. (1993). *Soils in the New Zealand Landscape: the living mantle.* Wellington: New Zealand Society of Soil Science

Moore, J. R. (2012). growing fit-for-purpose structural timber: What's the target and how do we get there? *New Zealand Journal of Forestry, 57*(3), 17-24.

Nelder, J. A. (1962). New kinds of systematic designs for spacing experiments. *Biometrics, 18*(3), 283-307.

Sorensson, C. T., & Shelbourne, C. J. A. (2005). *Clonal forestry*. New Zealand: Christchursh: New Zealand Institute of Forestry.

Waghorn, M. J., Watt, M. S., & Mason, E. G. (2007). Influence of tree morphology, genetics, and initial stand density on outerwood modulus of elasticity of 17-year-old Pinus radiata. *Forest Ecology and Management, 244*(1), 86-92.

Walford, G. B. (1985). The mechanical properties of New Zealand-grown radiata pine for export to Australia. *FRI Bulletin, Forest Research Institute, New Zealand, 93*(19).

Walker, J. C. F. (2006). *Primary Wood Processing: Principles and Practices (2nd ed.).* Netherlands: Springer.

Walker, J. C. F., & Butterfield, B. G. (1996). The importance of microfibril angle for the processing industries. *New Zealand Journal of Forestry, 40*, 34-40.

Warren, E., Smith, R. G. B., Apiolaza, L. A., & Walker, J. C. F. (2009). Effect of stocking on juvenile wood stiffness for three Eucalyptus species. *New Forests, 37*(3), 241-250.

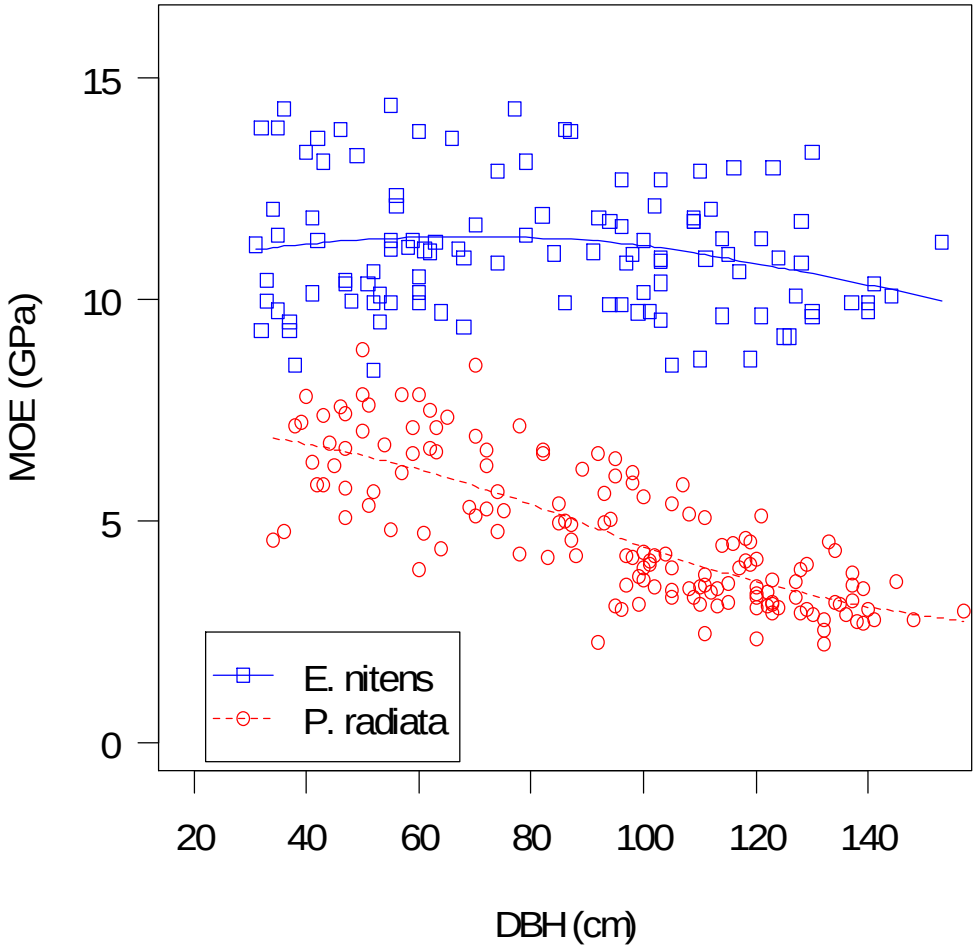
Watt, M. S., Moore, J. R., Facon, J. P., Downes, G. M., Clinton, P. W., Coker, G., . . . Bown, H. E. (2006). Modelling the influence of stand structural, edaphic and climatic influences on juvenile Pinus radiata dynamic modulus of elasticity. *Forest Ecology and Management, 229*(1), 136-144.

Xu, P., & Walker, J. C. F. (2004). Stiffness gradients in radiata pine trees. *Wood Science and Technology, 38*(1), 1-9.

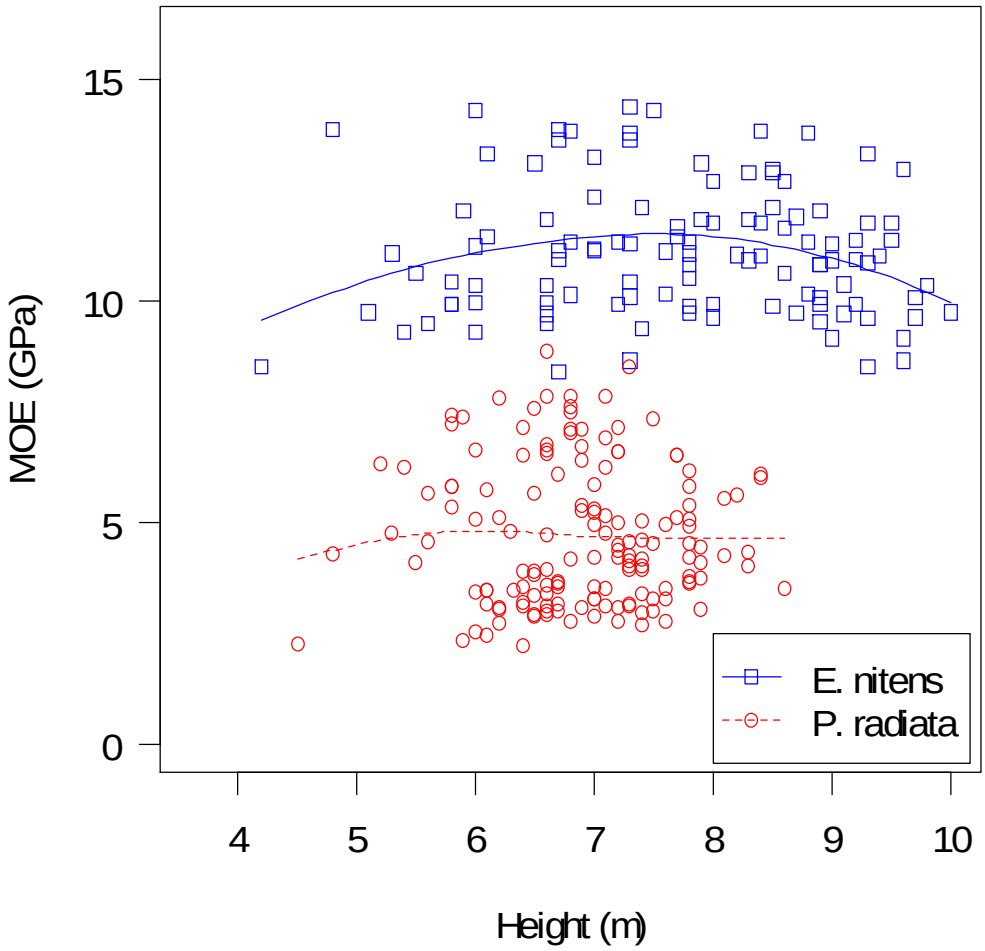
Yang, J. L., & Evans, R. (2003). Prediction of MOE of eucalypt wood from microfibril angle and density. *Holz als Roh- und Werkstoff, 61*(6), 449-452.

9.0 Appendices

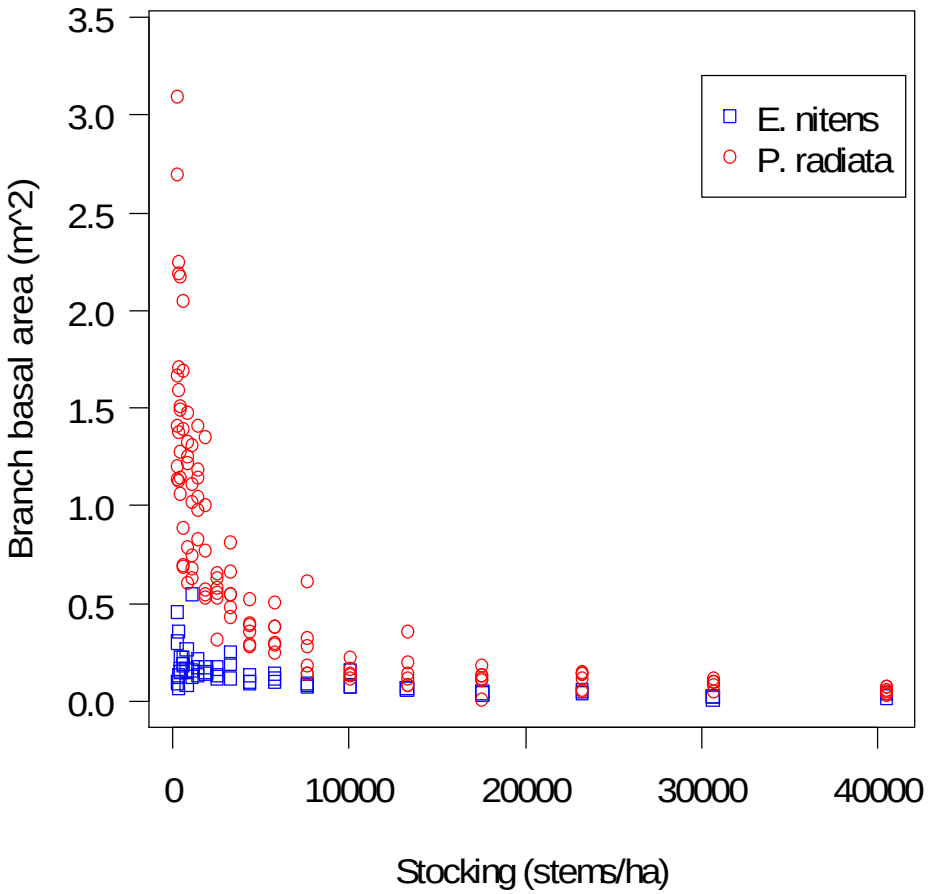
Appendix 1: Relationship between DBH and MOE.



Appendix 2: Relationship between tree height and MOE.



Appendix 3: Relationship between branch basal area per tree and stocking.



Appendix 4: Relationship between number of branches per tree and stocking.